A Multi-Verse Meshfree (MV-MF) Model for Optimal Pump-and-Treat Groundwater Remediation under Single and Multiple Objectives

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Abstract

In this study, multi-verse-meshfree (MV-MF) simulation-optimization model and its multi-objective version (MOMV-MF) were developed to find the appropriate groundwater remediation strategy by PAT method. These models compare with particle swarm meshfree (PS-MF) simulation-optimization model and its multi-objective version (MOPS-MF). In the one-objective optimization problem, the objective function was defined as minimizing the mean of contaminant concentration by pumping at a constant rate, while in the two-objectives problem, the pumping rate was variable and the mean of pumping rate from all the wells is minimized. Finally, minimizing the remediation period added to set of objective functions as third objective function. The results indicated that locating the pumping wells in the path of the contaminant flow and close to the source improves the efficiency of the PAT system. In one-objective optimization problems, the results indicated that the MV-MF and PS-MF models have same performance with 2.68033 and 2.68035, respectively. But PSO algorithm is trapped in local optimum. Besides, the MVO algorithm, with its special theory of traveling objects between two universes, can easily move from one part of the search space to another. In the two-objectives problem, the results indicated that the number of solutions in the pareto-front in MOMVO with 8 solution was higher than MOPSO with 4 solutions. In three-objectives problem, the results of MOMVO and MOPSO algorithm indicated that by changing the PAT policy, the 3 years (1095 days) remediation period can be reduced to 525 and 535 days, respectively. Also, one of the main findings of this research was good performance of MVO algorithm, because of the special way the algorithm works in transport the objects between different universes. The objects are nodes number and they can easily move between different universes but nodes number change in PSO algorithm by velocity vector.

Introduction

Groundwater is one of the most important sources of freshwater across the world and the lives of many people depend on it. Because these resources are located underneath the Earth's top crust, therefore, are poorly monitored and managed. Besides, the use of pesticides and fertilizers, seepage from landfills, and other human activities can easily contaminate groundwater. Therefore, groundwater quality protection has a high priority. Any study on groundwater pollution, including the groundwater contamination source identification, contaminant transport, and groundwater remediation can be a step towards groundwater quality protection.

The numerical methods such as finite difference method (FDM), finite element method (FEM) and meshless (Meshfree) method are more commonly used by researchers for groundwater flow modeling, contamination source identification, contaminant transport and groundwater remediation.

Many researchers have used numerical methods for Evaluation of Groundwater Storage Potentials Obiefuna and Eslamian, (2019), groundwater flow modeling Zeynali et al., (2025) and Zeynali et al., (2026) identifying the groundwater pollution sources using FEM Ghafouri and Darabi., (2007), contaminant transport modeling using FEM Javadi and Al-Najjar., (2007), identifying groundwater contamination sources using meshfree Guneshwor et al., (2018), investigating nitrate contaminant transport using FDM Fadlallah et al., (2019), contaminant transport problems with constant and oscillating boundary conditions using FDM Savovic and Djordjevich (2020), investigating the coupled simulation of groundwater flow and contaminant transport using a moving least squares based meshless element-free Galerkin method Pathania and Eldho., (2020) and groundwater remediation (Zeynali et al., 2024a; Zeynali et al., 2024b).

In recently years, groundwater remediation optimization problems have received much attention and some researchers have combined numerical methods with meta-heuristic algorithms in order to solve the groundwater remediation optimization problems. Combination genetic algorithm (GA) and MODFlOW software for pump-and-treat groundwater remediation Wang et al, (2018), particle swarm optimization (PSO) and meshfree for In-situ bioremediation of groundwater Mategaonkar et al., (2018), PSO and meshfree radial point collocation Method for groundwater remediation by PAT method Anshuman and Eldho., (2019), PSO and meshless element-free Galerkin method for in-situ bioremediation Pathania et al., (2020), GA, PSO, firefly algorithm (FA) and FEM for groundwater flow modeling Akbarpour et al, (2020a) and GA and FDM for the in-situ chemical oxidation as a remediation technique (Zeynali et al., 2022a).

To our best knowledge, it can be explained that the simultaneous consideration of different objectives in groundwater remediation is very important. Besides, it is essential to use an efficient S/O model that can be applied to real-world problems. Therefore, the purpose of this study is to provide S/O model that can find the best pumping wells location for the PAT system. So those different objectives such as minimizing the contaminant concentration, mean of pumping rate, and the treatment period are considered simultaneously. Due to the purpose of this study, we present MV-MF and MOMV-MF simulation-optimization model. Also, the S/O model can be determining optimal different arrangements of pumping wells at the aquifer domain. So that according to the importance of each objective in a specific real case study, the decision maker can choose one of those arrangements. But, one of the most important challenges in solving this problem is its high computational cost, considering the number of population members, the number of iterations, and the number of nodes in the aquifer domain.

Materials and Methods

Case Study

Ghaen basin with an area of 929.1 km^2 is located between longitudes 58° 53′ 39″ to 59° 24′ 40″ east and 33° 32′ 07″ to 33° 51′ 20″ north. The aquifer is recharged from the south and west and discharged from the east by 3.61 and 8.28 and 0.5 Mm^3/year, respectively. There is a contaminant resource with absorptive well. Through this absorptive well, chloride and nitrate-nitrogen contaminants seepage to groundwater. These contaminants have amounts higher than the standard of wastewater in Iran. The value of chloride concentration and nitrate-nitrogen concentration are 643.2 (mg/lit) and 19.6 (mg/lit), respectively. While, permissible limits for these contaminants are 600 (mg/lit) and 10 (mg/lit), respectively. This contaminant source polluted the aquifer for 5 years from 2016 to 2020. Figure (1) shows the position of the contaminant source and recharge and discharge zones. Also, there are 134 pumping wells in the Ghaen aquifer. Due to the aquifer grid and distance between nodes (200 m), 17 number of pumping wells were placed in nearest nodes and their pumping rate were added together. Five-days' time step is chosen for both the groundwater flow and the contaminant transport model. In order to using hydraulic information for aquifer modeling, at first, we create Thiessen polygon for hydraulic conductivity using ArcGIS software. The

boundary line and the nodes with constant flow (blue rhombuses) as Neumann boundary are shown in Figure (2). The location of contaminant concentration is also shown in this figure (Zeynali et al., 2022b).

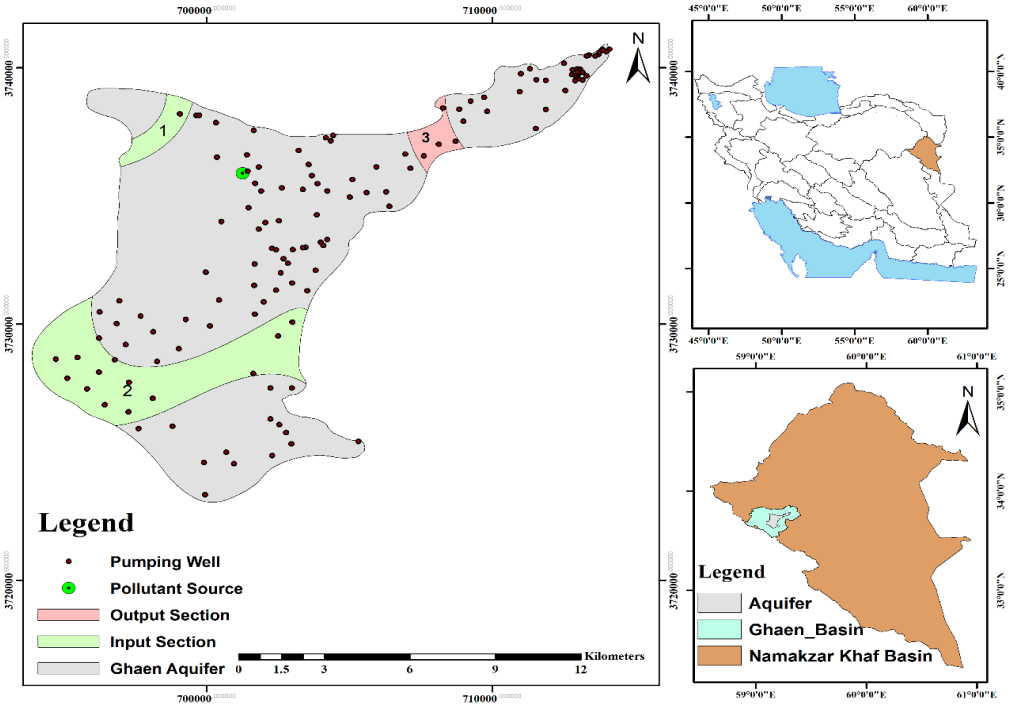


Fig. 1- Location map of the study area

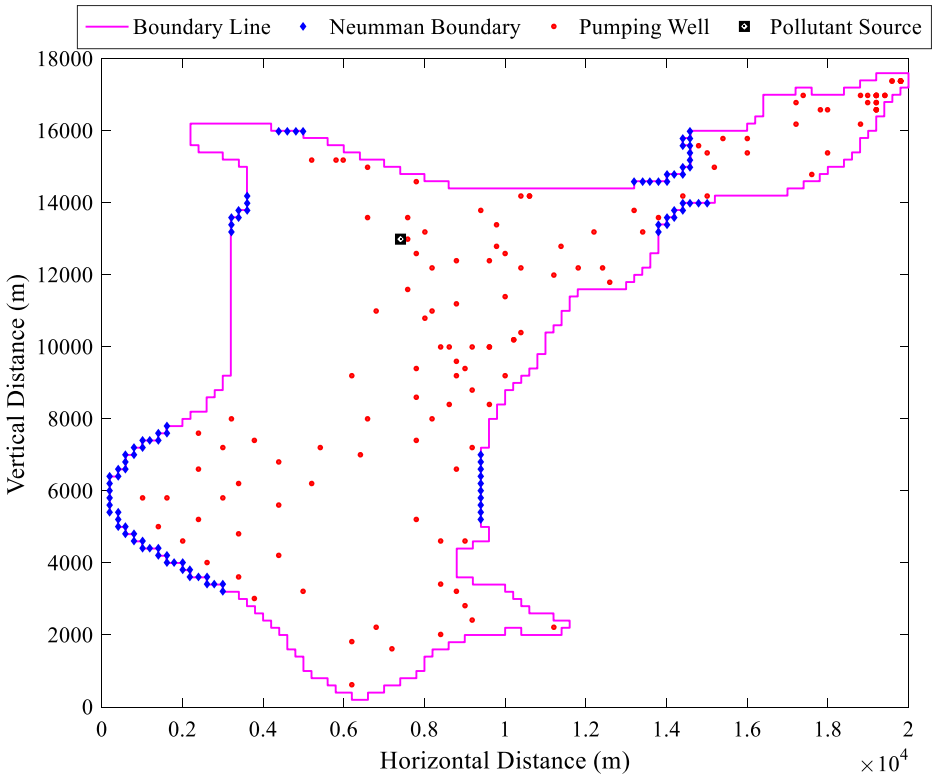


Fig. 2- Neumann boundary, pumping wells and contaminant source

There are various methods for water and soil contaminated remediation, including pump and treat, soil vapor extraction, solidification/stabilization, chemical oxidation, soil flushing, electrokinetic separation, bioventing, phytoremediation, etc. In the pump and treat method, contaminated water is extracted through pumping wells and then remediation is performed. After treatment in contaminated water at the surface, it can be used in agriculture or transferred into the Aquifer through injection wells or as flood spreading. Now, the main issue in this method is finding the pumping wells location should be performed to maximize the efficiency of the PAT system or in other words, help us achieve our purpose.

Objective Functions

PAT system costs depend on the residual contaminant concentration at the end of the remediation period. Three objective functions are considered in this case study. These objective functions are (1) Minimizing the contaminant concentration, (2) Minimizing the mean of pumping rate and (3) Minimizing the remediation period. Therefore, the purpose of this study is finding the optimal location of pumping wells so that objective functions are minimized. The objective functions are defined mathematically as follows:

$$MinF_1 = \left(\sum_{k=1}^{K} C_k\right)/K \tag{1}$$

$$MinF_2 = \frac{\sum_{j=1}^{J} {q_j}^{Ex}}{J} \tag{2}$$

$$MinF_3 = remediationperiod \tag{3}$$

Where F_1 to F_3 are the objective functions 1 to 3, respectively. In the first objective function minimizes the mean of contaminant concentration where, K is number of nodes and C_k is contaminant concentration in k^{th} nodes. In the second objective function minimizes the mean of pumping rate of all wells (m^3/day). J is the number of pumping wells and q_j^{Ex} is the pumping rate at j^{th} pumping well (m^3/day). The third objective function (F_3) consists in minimizing the remediation period.

In one-objective problem, we use F_1 as objective function and four pumping wells at a rate of 800 m^3/day (pumping at a constant rate) and the remediation period will be three years. In two-objectives problem, we use F_1 and F_2 as objective functions and the pumping rate is in range [500,800] m^3/day for four pumping wells. Also, the remediation period is 3 years. In three-objectives problem pumping, we consider the conditions of the two-objective problem, with the difference that the remediation period will be from one to three years.

Governing Equations

Groundwater Flow Modeling

The governing partial differential equations describing the steady-state flow in a two-dimensional inhomogeneous, anisotropic confined and unconfined aquifers are given as (Wang and Anderson., 1982):

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial H}{\partial y}\right) = R \tag{4}$$

$$\frac{\partial}{\partial x}\left(k_x H \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y H \frac{\partial H}{\partial y}\right) = R \tag{5}$$

Moreover, the governing partial differential equations describing the Transient flow in a two-dimensional inhomogeneous, anisotropic confined and unconfined aquifers are given as (Wang and Anderson., 1982):

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + Q_w \delta(x - x_i)(y - y_i) - q \tag{6}$$

$$\frac{\partial}{\partial x}\left(K_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y h \frac{\partial h}{\partial y}\right) = S_y\frac{\partial h}{\partial t} + Q_w \delta(x - x_i)(y - y_i) - q \tag{7}$$

where h(x,y,t) or H(x,y,t) is the piezometric head [L], T_i(x,y) is anisotropic

transmissivity [L^2T^{-1}]; $K_i(x,y)$ is anisotropic hydraulic conductivity [LT^{-1}]; $S(x,y)$ is storage coefficient, $S_y(x,y)$ is specific yield; Q_w is source or sink function; ($-Q_w$ = source and Q_w = sink) [LT^{-1}]; δ is Dirac delta function; x_i and y_i are the pumping or recharge well location; $q(x,y,t)$ is vertical inflow rate [LT^{-1}]; x and y are horizontal space variables [L] and t is the time [T].

Meshfree Method to Solve Governing Equations for Groundwater Flow

The first step is to define an approximate value. The approximate value for head is:

$$H = \sum_{i=1}^{m} H(t) \times \phi_i(x,y) \tag{8}$$

Using weighted residual method we have:

$$\begin{aligned} &-2k\left[\iint_\Omega \frac{\partial W_i}{\partial x} H \times H \frac{\partial \phi}{\partial x} d\Omega \right. \\ &\left. + \iint_\Omega \frac{\partial W_i}{\partial y} H \times H \frac{\partial \phi}{\partial y} d\Omega\right] \\ &= 2\iint_\Omega W_i S_y \frac{\partial H}{\partial t} d\Omega + 2\iint_\Omega W_i R d\Omega \end{aligned} \tag{9}$$

$$\begin{aligned} &-2k\left[\iint_\Omega \frac{\partial W_i}{\partial x} H^{n+1} \times H^n \frac{\partial \phi}{\partial x} d\Omega \right. \\ &\left. + \iint_\Omega \frac{\partial W_i}{\partial y} H^{n+1} \times H^n \frac{\partial \phi}{\partial y} d\Omega\right] \\ &= 2\iint_\Omega W_i S_y \left(\frac{H^{n+1} - H^n}{\Delta t}\right) d\Omega \\ &\qquad + 2\iint_\Omega W_i R d\Omega \end{aligned} \tag{10}$$

$$\begin{aligned} &-2k\left[\iint_\Omega \frac{\partial W_i}{\partial x} H^{n+1} \times H^n \frac{\partial \phi}{\partial x} d\Omega \right. \\ &\left. + \iint_\Omega \frac{\partial W_i}{\partial y} H^{n+1} \times H^n \frac{\partial \phi}{\partial y} d\Omega\right] \\ &-2\iint_\Omega W_i S_y \left(\frac{H^{n+1}}{\Delta t}\right) d\Omega \\ &= -2\iint_\Omega W_i S_y \left(\frac{H^n}{\Delta t}\right) d\Omega + 2\iint_\Omega W_i R d\Omega \end{aligned} \tag{11}$$

$$\begin{aligned} &\left(-2k\left[\iint_\Omega \frac{\partial W_i}{\partial x} H^n \frac{\partial \phi}{\partial x} d\Omega \right. \right. \\ &\left. + \iint_\Omega \frac{\partial W_i}{\partial y} H^n \frac{\partial \phi}{\partial y} d\Omega\right] \\ &\left. -2\iint_\Omega W_i S_y \left(\frac{1}{\Delta t}\right) d\Omega\right) \times H^{n+1} \\ &= -2\iint_\Omega W_i S_y \left(\frac{H^n}{\Delta t}\right) d\Omega + 2\iint_\Omega W_i R d\Omega \end{aligned} \tag{12}$$

This equation is similar to the linear equation:

$$\begin{aligned} [K] = &-2k\left[\iint_\Omega \frac{\partial W_i}{\partial x} H^n \frac{\partial \phi}{\partial x} d\Omega \right. \\ &\left. + \iint_\Omega \frac{\partial W_i}{\partial y} H^n \frac{\partial \phi}{\partial y} d\Omega\right] \\ &-2\iint_\Omega W_i S_y \left(\frac{1}{\Delta t}\right) d\Omega \end{aligned} \tag{13}$$

$$[U] = H^{n+1} \tag{14}$$

$$\begin{aligned} [F] = &-2\iint_\Omega W_i S_y \left(\frac{H^n}{\Delta t}\right) d\Omega \\ &+ 2\iint_\Omega W_i R d\Omega \end{aligned} \tag{15}$$

The force matrix in the last equation determines the amount of recharge and discharge. It indicates the rate of recharge or discharge of the aquifer. In other words, this matrix shows the interaction or extraction flow rate in two concentrated and distributed conditions.

$$\begin{aligned} [F] = &-2\iint_\Omega W_i S_y \left(\frac{H^n}{\Delta t}\right) d\Omega \\ &+ 2\iint_\Omega W_i R d\Omega \\ = &-2\iint_\Omega W_i S_y \left(\frac{H^n}{\Delta t}\right) d\Omega \\ &+ \iint_\Omega W_i Q_k \delta(x - x_k)(y \\ &- y_k) d\Omega \\ &+ \iint_\Omega W_i q d\Omega \end{aligned} \tag{16}$$

Contaminant Transport Modeling

The governing differential equation is obtained based on the mass balance of any particular solute in a control volume of

porous media. The final unsteady form of the equation, including adsorption and other chemical reactions, is written as follows (Ghafouri and Darabi., 2007):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right) - v_x \frac{\partial C}{\partial x} - v_y \frac{\partial C}{\partial y} - v_z \frac{\partial C}{\partial z} + CHEM \quad (17)$$

The seepage velocity required to the solute-transport model is calculated using Darcy's law (Bear 1972) and is written as: $V_i = -\frac{K_i}{\theta}\frac{\partial h}{\partial x_i}$, $i = x, y$; where $V_i(x,y)$ is the seepage velocity in i-direction [LT^{-1}]; and θ = porosity.

In which C is the concentration of contamination at any given time and space, D the dispersion coefficient and V is the seepage velocity. The first three terms at RHS show the dispersion phenomena while the second three terms represent the advection of contaminant. Also, CHEM is consisting of the followings (Ghafouri and Darabi., 2007):

$$CHEM = -\frac{\rho_b}{n}\frac{\partial s}{\partial t} \quad (18)$$

Which indicates the superficial forces of adsorption and ionization processes, and

$$CHEM = -\lambda\left(C + \frac{\rho_b}{n}s\right) \quad (19)$$

In the above equations ρ_b is the bulk soil density (ML^{-3}), λ is constant decay coefficient (T^{-1}), s is the density of absorbed substance on soil grains or colloids, and *n* is the soil porosity. Substituting these terms into Eq. 16 and simplifying them, results in the following equation (Ghafouri and Darabi., 2007):

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{n}\frac{\partial s}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right) - v_x \frac{\partial C}{\partial x} - v_y \frac{\partial C}{\partial y} - v_z \frac{\partial C}{\partial z} - \lambda\left(C + \frac{\rho_b}{n}s\right) \quad (20)$$

Assuming s = k_d × C, where k_d is a distribution coefficient, applying the chain rule to the derivative of s and re-ordering the resulted relations, Eq. 19 may be written as follows:

$$R\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right) - v_x \frac{\partial C}{\partial x} - v_y \frac{\partial C}{\partial y} - v_z \frac{\partial C}{\partial z} - R\lambda C \quad (21)$$

Eq. (16) is three dimensional governing equation of advection-dispersion of contaminants in groundwater resources where $R = 1 + \frac{\rho_b k_d}{n}$ is the retardation factor with ρ_b = media bulk density [ML^{-3}], and K_d = sorption coefficient [L^3M^{-1}]; C(x,y,t) is solute concentration [ML^{-3}]; D_x and D_y are components of dispersion coefficient tensor [L^2T^{-1}]; λ is the reaction rate constant [T^{-1}]. For transient flow and transport analysis, the following initial conditions are used:

$$h(x,y,0) = h_0(x,y); \quad C(x,y,0) = fx, y \in \Omega \quad (22)$$

The flow and transport equations should be solved with appropriate boundary conditions. The boundary conditions can be written as (Eldho and Swathi., 2018):

$$h(x,y,t) = h_1(x,y,t); \quad C(x,y,t) = g_1 x, y \in \Gamma_1 \quad (23)$$

$T\frac{\partial h}{\partial n} = q_1(x,y,t)$ is for confined aquifer, $Kh\frac{\partial h}{\partial x} = q_2(x,y,t)$ is for unconfined aquifer:

$$\left(D_x \frac{\partial C}{\partial x}\right) n_x + \left(D_y \frac{\partial C}{\partial y}\right) n_y = g_2 x, y \in \Gamma_2 \quad (24)$$

where Ω is flow region; $\Gamma = \Gamma_1 \cup \Gamma_2$ is region boundary; $\frac{\partial}{\partial m}$ is normal derivative; $h_0(x,y)$ is initial head in the flow domain [L]; $h_1(x,y,t)$ is known head value at the boundary section Γ_1 [L]; f is a given function in Ω, g_1 and g_2 are given functions along boundary sections Γ_1 and Γ_2 ; and $n_x n_y$ are the components of the unit outward normal vector to the boundary section Γ_2.

Meshfree Method to Solve Governing Equation for Transport

The approximate value for concentration is:

$$C(x,y,t) = \sum_{i=1}^{m} C(t) \times \phi(x,y) \quad (25)$$

Where $\phi(x,y,z)$ is an arbitrary approximating function. Applying the meshfree method to the Eq. (25) leads to a set of simultaneous algebraic equations as:

$$[A]\{C\}^{t+\Delta t} = [B]\{C\}^t + \{f\} \quad (26)$$

Where:

$$[A] = [K] + [U] + [F] + [q] + [c'] + \frac{1}{\Delta t}[P] \quad (27)$$

$$[B] = \frac{1}{\Delta t}[P] \quad (28)$$

Δt is the length of time interval, the so-called time-step, $\{C\}^t$ is the vector of known concentrations at the beginning of any time step and $\{C\}^{t+\Delta t}$ is the vector of sought unknown concentrations at the end of time step. [G], [U], [F] and [P] are square matrices. The elements of these matrices are computed as followings:

$$[K] = \iint_\Omega D_x \frac{\partial W_i}{\partial x}\frac{\partial \phi}{\partial x} d\Omega + \iint_\Omega D_y \frac{\partial W_i}{\partial y}\frac{\partial \phi}{\partial y} d\Omega \quad (29)$$

$$[P] = \iint_\Omega W_i \phi R d\Omega \quad (30)$$

$$[F] = -\iint_\Omega W_i R \lambda \phi d\Omega \quad (31)$$

$$[U] = -\left(\iint_\Omega W_i v_x \frac{\partial \phi}{\partial x} d\Omega - \iint_\Omega W_i v_y \frac{\partial \phi}{\partial y} d\Omega\right) \quad (32)$$

$$[q] = -\iint_e \frac{q_w}{\theta} . W_i \phi d\Omega \quad (33)$$

$$[c'] = -\iint_e \frac{w}{\theta . b} . W_i \phi R d\Omega \quad (34)$$

$$\{f\} = -\int_\Gamma (D_x \frac{\partial \phi}{\partial x} n_x + D_y \frac{\partial \phi}{\partial y} n_y) C^n W_i d\Gamma \quad (35)$$

Particle Swarm Optimization (PSO) Algorithm

In this algorithm, the position of each particle shows a point in the space of problem. Each particle has a memory and remembers the best position it finds in the space of problem. The movement of each particle can take place in three directions: 1-Continuation of its movement, in the same direction. 2-Move to the best position it has. 3-Move to the best position found by the entire group (all particles). In an optimization problem, each particle in the group can be showed by a velocity vector and a position vector (Mohamad Reza Pour et al., 2016).

Multi-Verse Optimization (MVO) Algorithm

Multi-Verse algorithm is a population-based algorithm. This algorithm divides the search process into two phases of exploration and exploitation. In this algorithm, the concepts of white hole and black hole are used to explore the search space. Besides, wormholes help exploit search spaces. Each solution is analogous to a universe and each variable in the solution is an object in that universe. In addition, an inflation rate is set

for each solution, which is proportional to the value of the objective function (Mirjalili et al., 2016).

During optimization, the following rules are applied to the universes of MVO (Mirjalili et al., 2016):

1. The higher inflation rate means higher probability of having white holes.
2. The higher inflation rate means tend to send objects through white holes.
3. Universes with higher inflation rate tend to send objects through white holes.
4. Universes with lower inflation rate tend to receive more objects through black holes.
5. The objects in all universes may face random movement towards the best universe via wormholes regardless of the inflation rate.

PSO and MVO algorithms are mainly used to solve continuous problems. Although discrete versions of these algorithms can also be developed and used. However, in this study, the node number that determines the location of the pumping wells is obtained by rounding the number.

Flowchart of Optimization-Simulation Problem

The steps of solving the optimization-simulation problem for a single-objective problem using the PSO and MVO algorithms are shown in Figure (3) and Figure (4), respectively. The flowchart for solving multi-objective problems is also similar to this flowchart.

Results and Discussion

The real aquifer has been investigated using meshfree. The results of groundwater flow and Chloride and Nitrate-Nitrogen concentration transport modeling for 5 years are presented in Figure (5) to Figure (7). the real aquifer is considered with pumping wells.

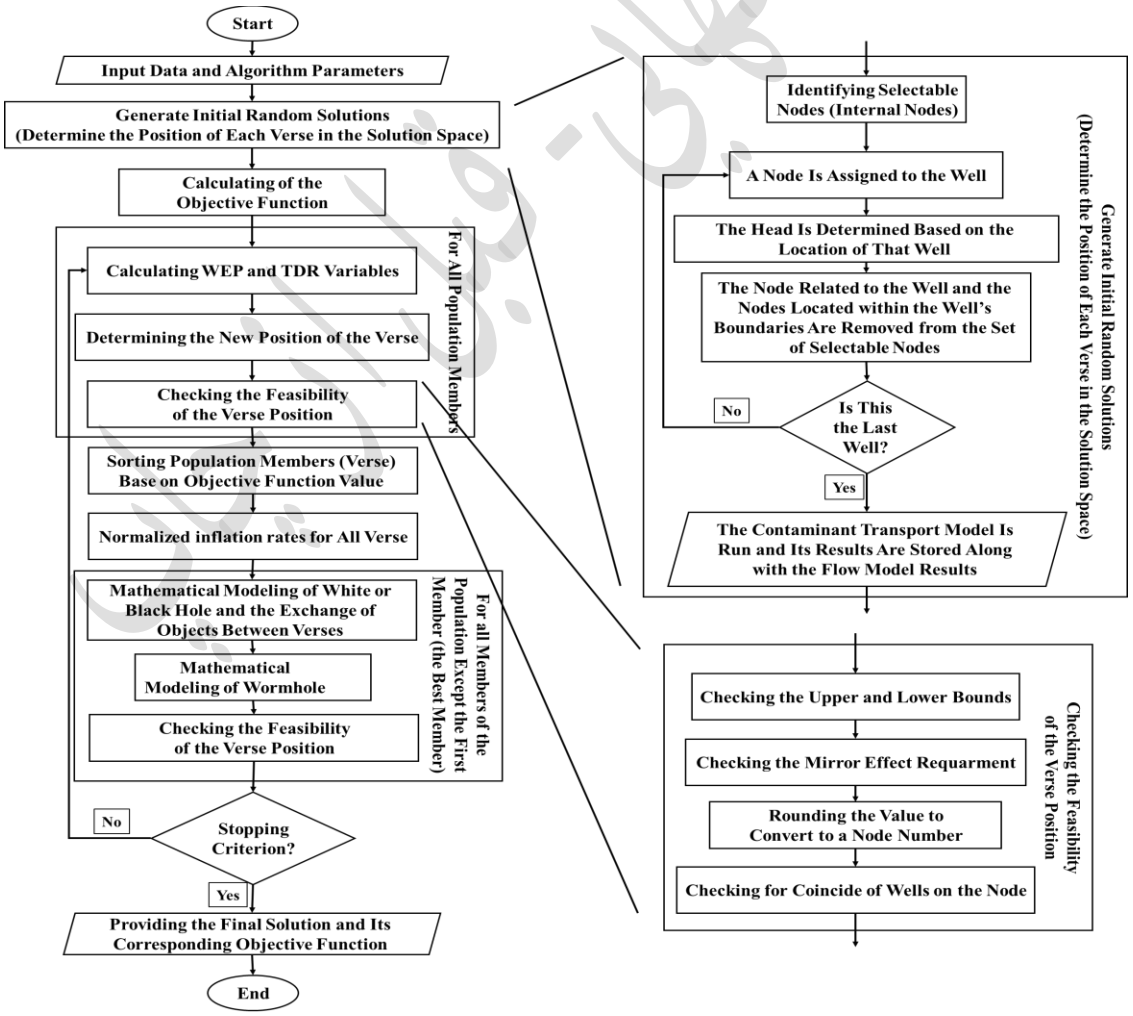


Fig. 3- Flowchart for modeling by PSO

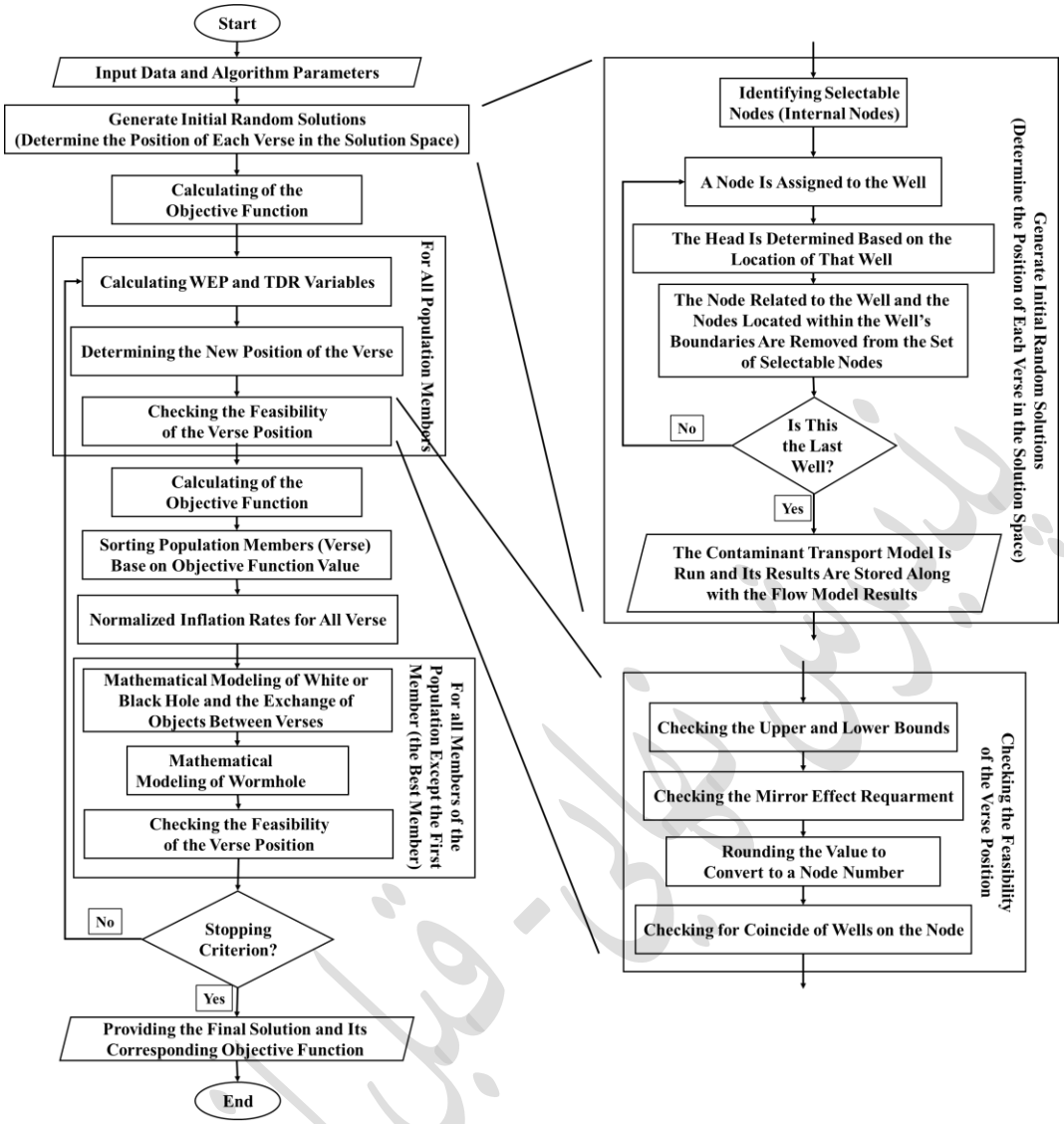


Fig. 4- Flowchart for modeling by MVO

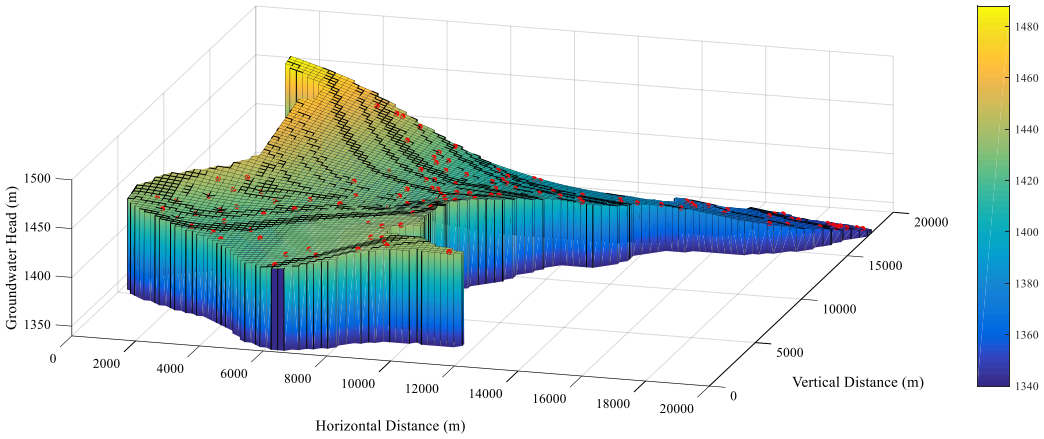


Fig. 5- Groundwater distribution after 5 years

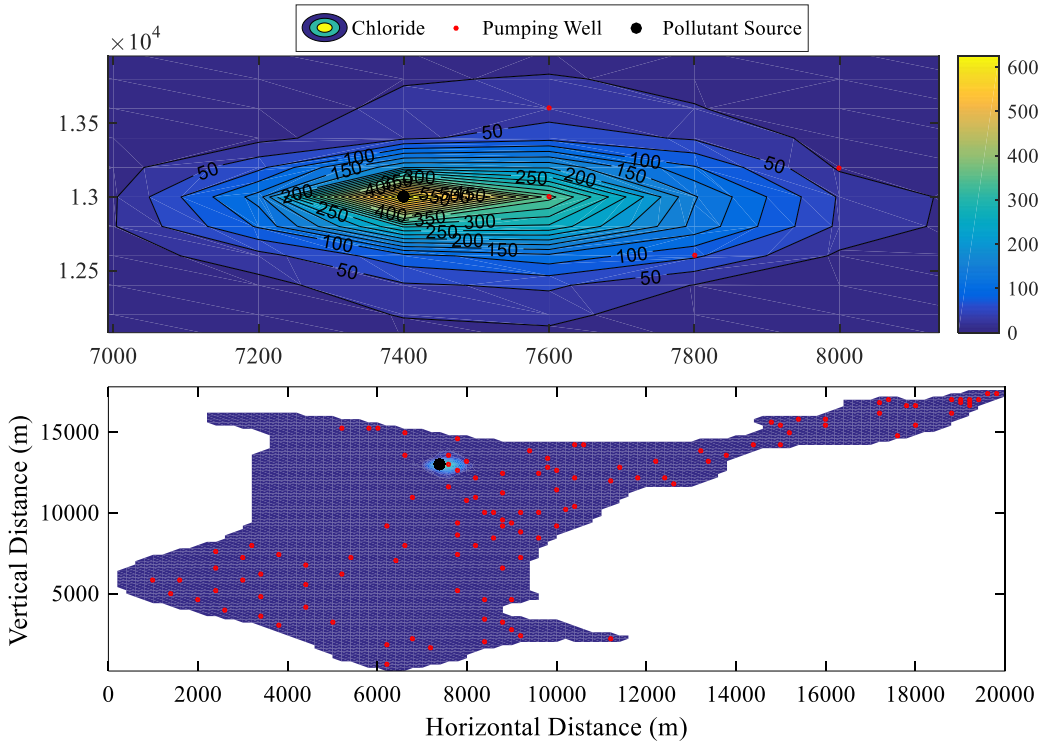


Fig. 6- Chloride concentration distribution after 5 years

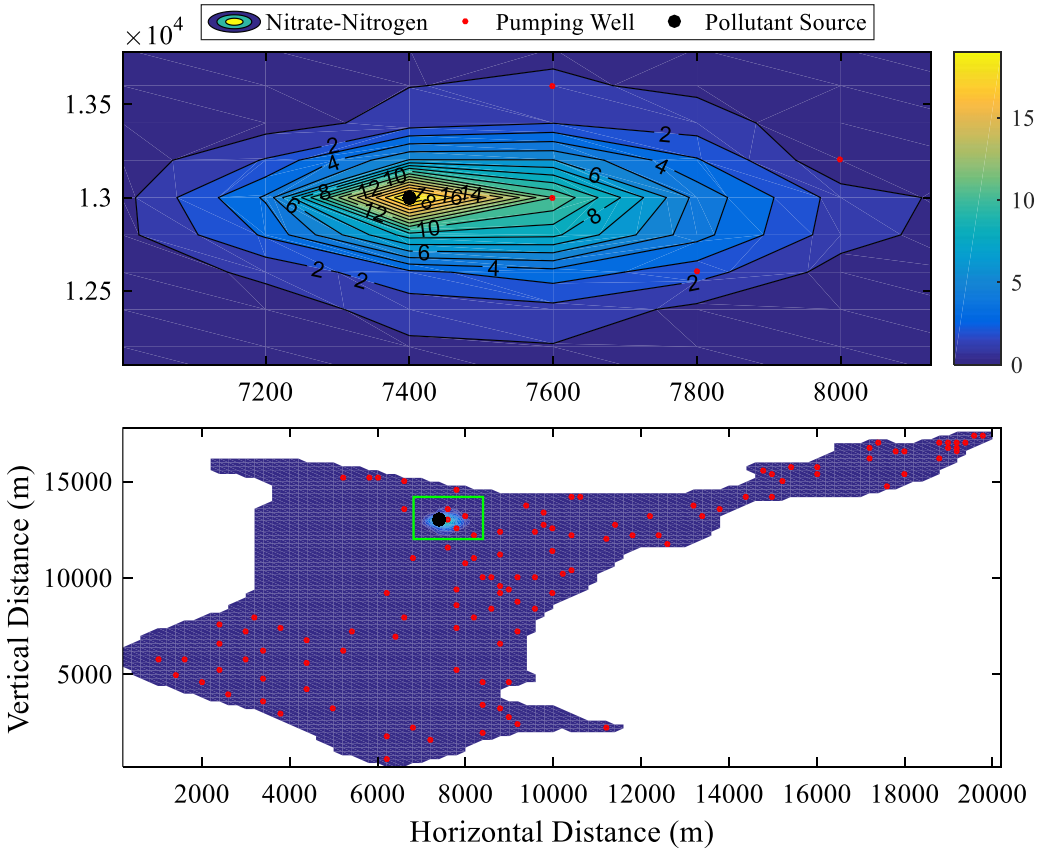


Fig. 7- Nitrate-Nitrogen concentration distribution after 5 years

The Results of One-Objective Optimization Problem

The first step of contaminant remediation is removing or modifying the source of the contaminant. Therefore, we assumed that there is no seepage from the source after 2020. In one-objective optimization problem we find the location of pumping wells to calculate the minimum of the first objective function.

In this case, the contamination concentration affects only a small part of the aquifer. Therefore, it is not necessary to explore the entire aquifer domain. However, we limited the search domain to determine the best location of the pumping wells as a heuristic information. New search domain has 2200 m length (north to south) and 1600 m width (east to west). The nodal arrangement is 12×9 and distance between nodes is 200 m. Therefore, members of the population in the PSO and MVO search only this domain. Also, we assumed 20 nodes around the contaminant source for calculating the first objective function. The remediation period is considered 3 years after preventing contaminant seepage. Monitoring nodes were also considered around the contaminant source. Population size and maximum iteration for PSO and MVO were 10 and 20, respectively. The results of these algorithms shown in Figure (8) and Figure (9). Due to these figures, it can be said PSO algorithm is trapped in a local optimum. Also, the statistical characteristics of the PSO and MVO performance is given in Table (1). Due to this table, it can be said that two algorithms had a same performance.

The pumping well's location, with pumping at the rate 800 m^3/day, (red circle marker) and the Chloride concentration after 3 years remediation for the 5th run of PSO algorithm and Nitrate-Nitrogen concentration after 3 years remediation for the 5th run of MVO algorithm are shown in Figure (10) and Figure (11), respectively. As can be seen in these figures, the best location of pumping wells is in the path of the contaminant flow and close to the source. When the contamination mass is moving to the right and bottom side of the aquifer, the algorithms located all wells in front of that to pumping most of the contaminants. As it can be seen in Figure (11) one of the pumping wells is located on the pumping well for agricultural use. Therefore, in multi-objective problems, nodes in which there are wells for agricultural use, similar to nodes located at the aquifer boundary, are removed from the selectable nodes for algorithm.

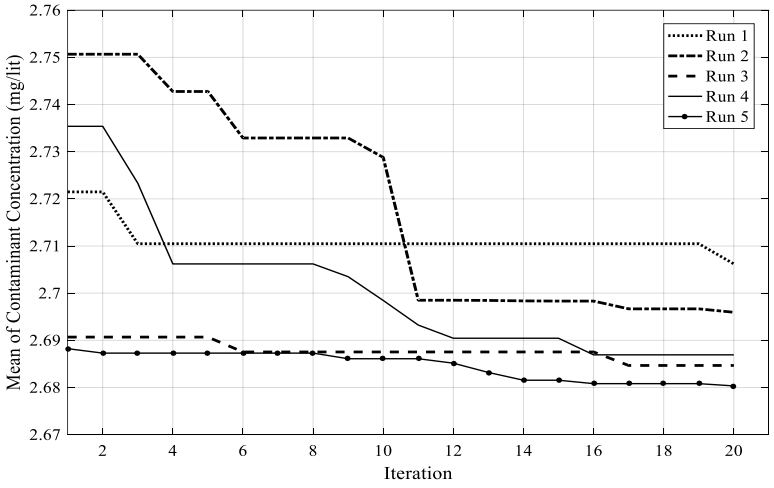


Fig. 8- The convergance trend of PSO algorithm

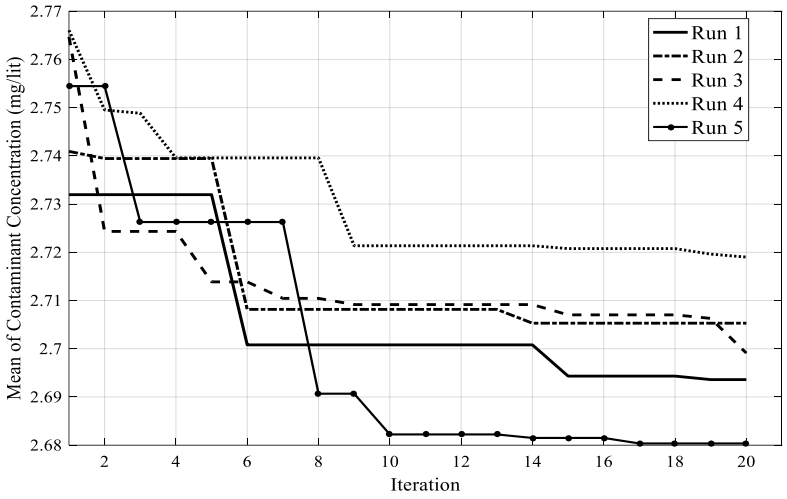


Fig. 9- The convergance trend of MVO algorithm

Table 1- Statistical characteristics of the PSO and MVO performance

Algorithm	The Best Value	The Worst Value	Average Values	Standard Deviation
PSO	2.68033	2.70620	2.69082	0.00923
MVO	2.68035	2.71900	2.69947	0.01277

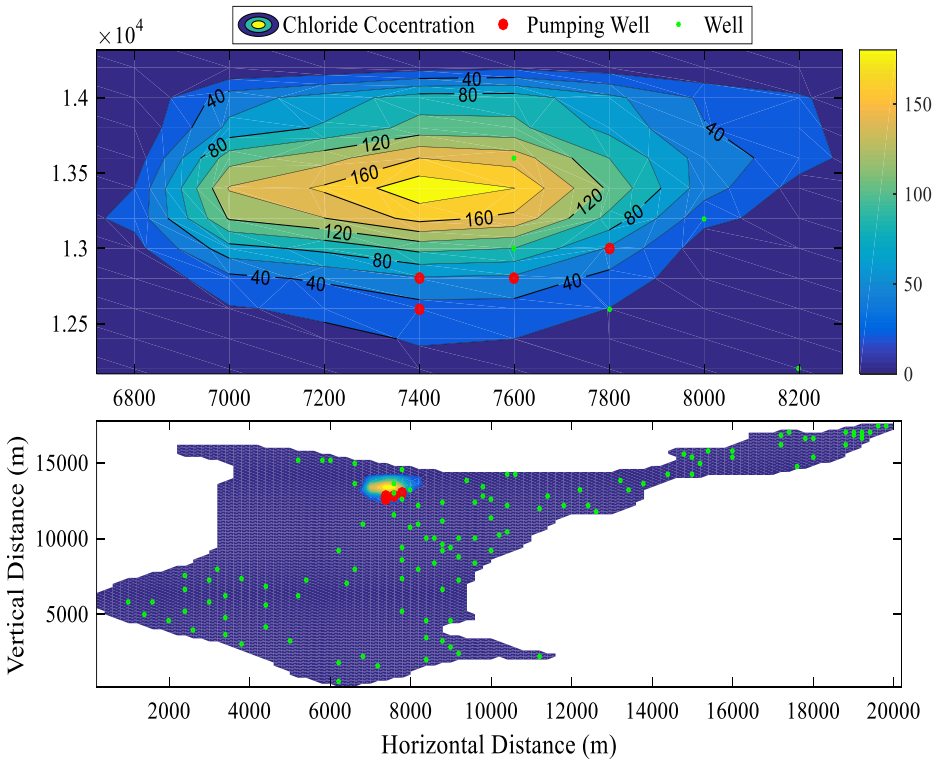


Fig. 10- Chloride concentration after 3 years remediation (PSO)

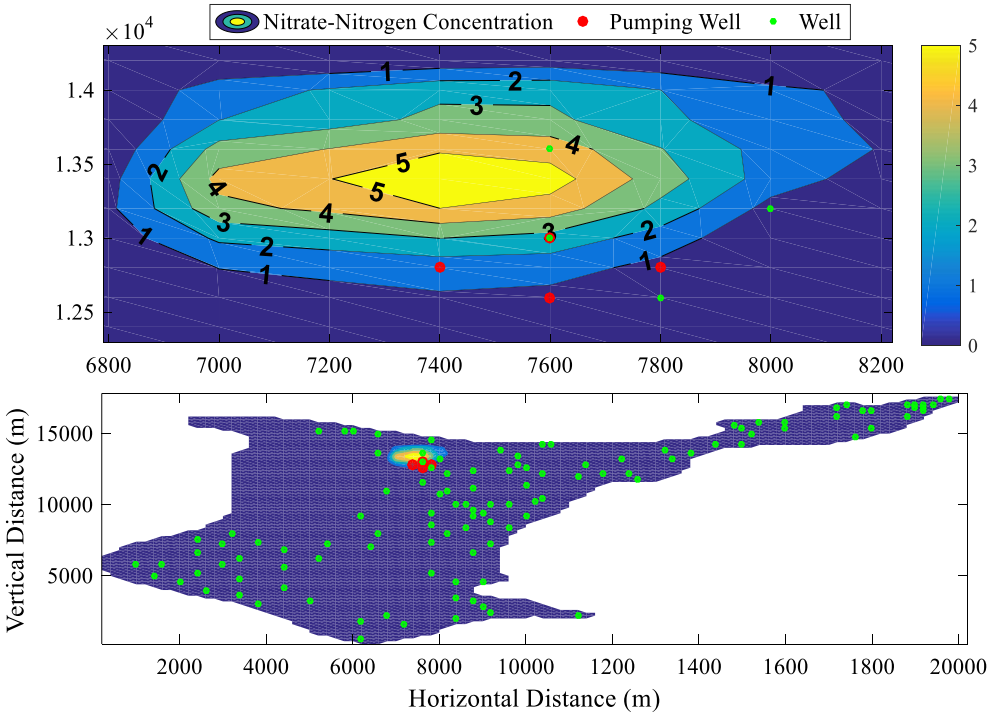


Fig. 11- Nitrate-Nitrogen concentration after 3 years remediation (MVO)

The Results of Two-Objective Optimization Problem

In Two-Objective optimization problem, we find the best location of wells to find the minimum of contaminant concentrations and mean of pumping rate. Therefore, MOPSO and MOMVO algorithm is able to get any value as pumping rate in a range of [500,800] m^3/day. In this case the nodes with pumping wells for agriculture use is removed from the selectable nodes similar to boundary nodes. Optimal Pareto-front for MOPSO and MOMVO are shown in Figure (12). Due to this figure, Number of solutions in Pareto-front for MOPSO and MOMVO is 4 and 8, respectively.

As shown in Figure (12). The number of solutions on the optimal pareto-front for the MOMVO algorithm is more than MOPSO. But the MOPSO algorithm has further covered the pareto-front with the solutions it has provided. Besides, by comparing the solutions that have the minimum value of the first objective function (mean of contaminant concentration), MOPSO algorithm has endured more than 100 m^3/day of additional pumping for these three years to reduce the mean of contamination concentration to 0.0044 mg/lit. However, in general, it can be said that the solutions provided by the MOMVO algorithm have dominate the solutions of the MOPSO algorithm. Therefore, it can be said that MOMVO algorithm has performed better than MOPSO algorithm in solving two-objective problem.

Also, performance criteria such as spacing (S), dispersion (Δ), convergence (γ), and generation distance (GD) Akbarpour et al., (2020b) are given in Table (2). The values of the performance criteria also indicate the higher efficiency of the MOPSO algorithm.

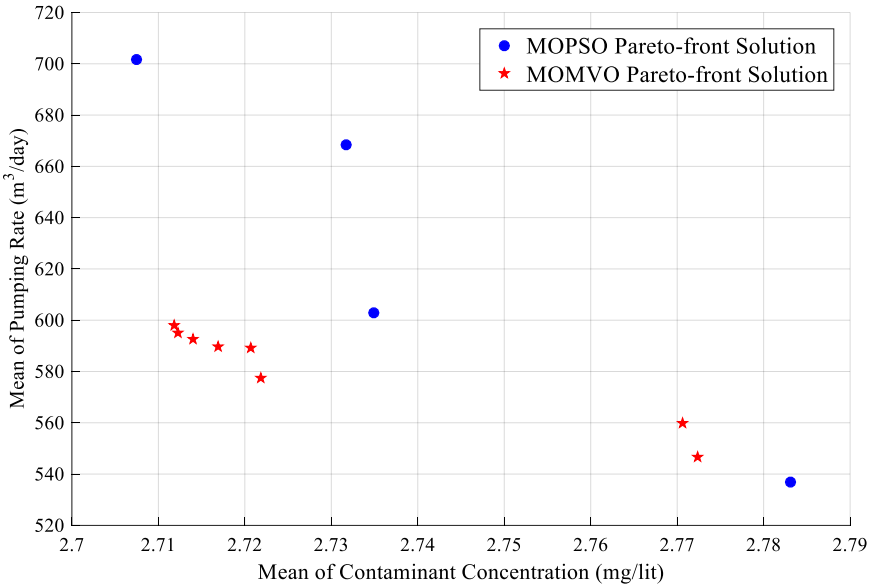


Fig. 12- Comparison of the Pareto fronts of MOPSO and MOMVO

Table 2- Performance criteria for PSO and MVO in two objective function problem

Algorithm	PSO	MVO
Number of Solution	4	8
S	30.75	6.15
Δ	0.6632	0.8444
γ	41.23	6.41
GD	27.27	3.16

The Results of Three-Objective Optimization Problem

In this case, MOPSO and MOMVO algorithms are able to get any value as pumping rate in a range of [500,800] m^3/day. Also, remediation period is considered in a range of [1,3] years with $\Delta T = 5\ days$. Population size and maximum iteration for these two algorithms were 10 and 20, respectively. The pareto-front of MOPSO and MOMVO algorithms are shown in Figure (13) and Figure (14), respectively.
Each of these solutions can be a groundwater remediation alternative for the PAT system. As shown in Figure (13) and due to $\Delta T = 5\ days$, changing the remediation policy from one option to another can reduce the remediation period 1.4 year (530 days). Also, due to Figure (14) and $\Delta T = 5\ days$, the interval between maximum and minimum of remediation period is 1.1 year (405 days). As can be seen in Figures (13) and (14), the number of solutions on the optimal pareto-front for the MOMVO algorithm is more than the MOPSO algorithm. Also, MOMVO algorithm in comparison with MOPSO algorithm has been able to provide a solution in which the remediation period has the shortest time. One of the solutions located in the optimal pareto-front is selected for MOPSO and MOMVO algorithms. The location of pumping wells and the contaminant concentration distribution of Chloride and Nitrate-nitrogen are shown in Figure (15) and Figure (16), respectively.

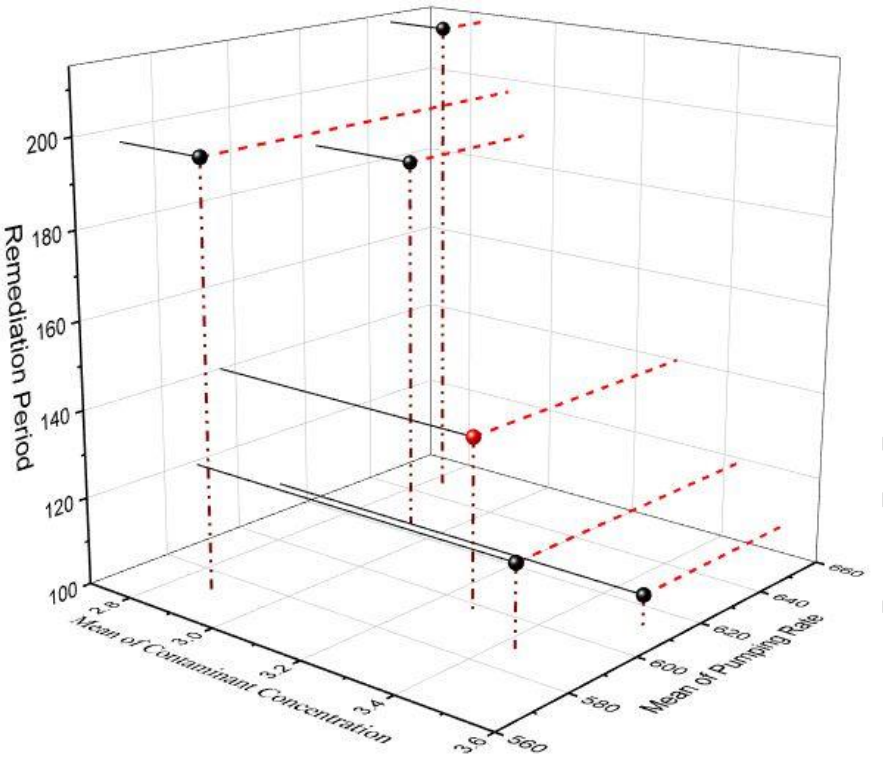


Fig. 13- Pareto front of MOPSO algorithm in three objective function

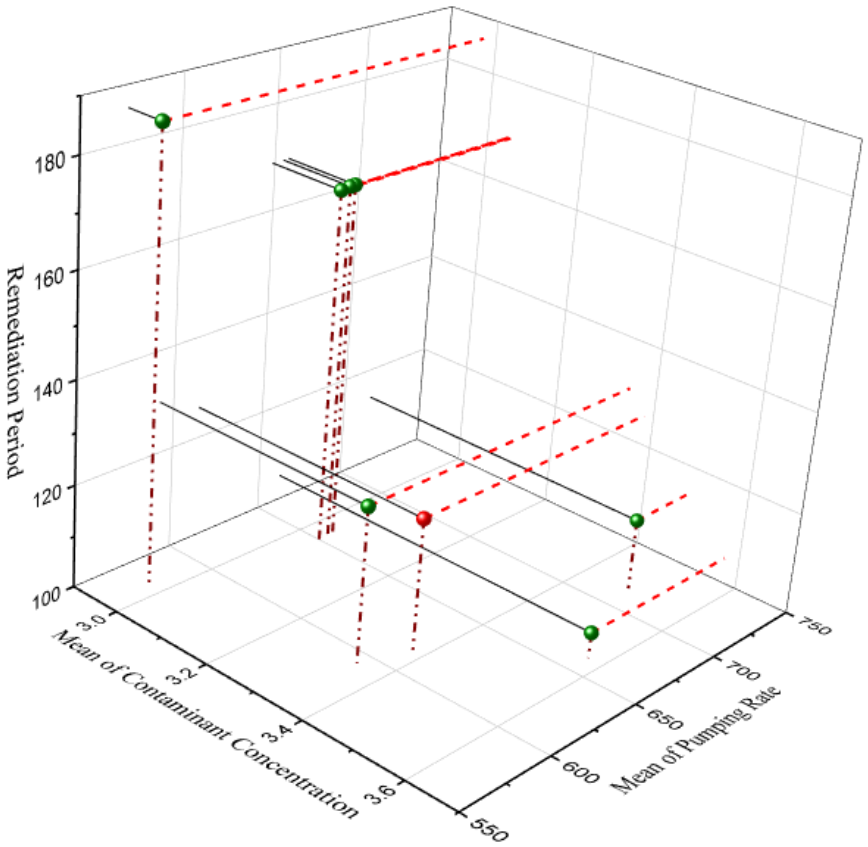


Fig. 14- Pareto front of MOMVO algorithm in three objective function

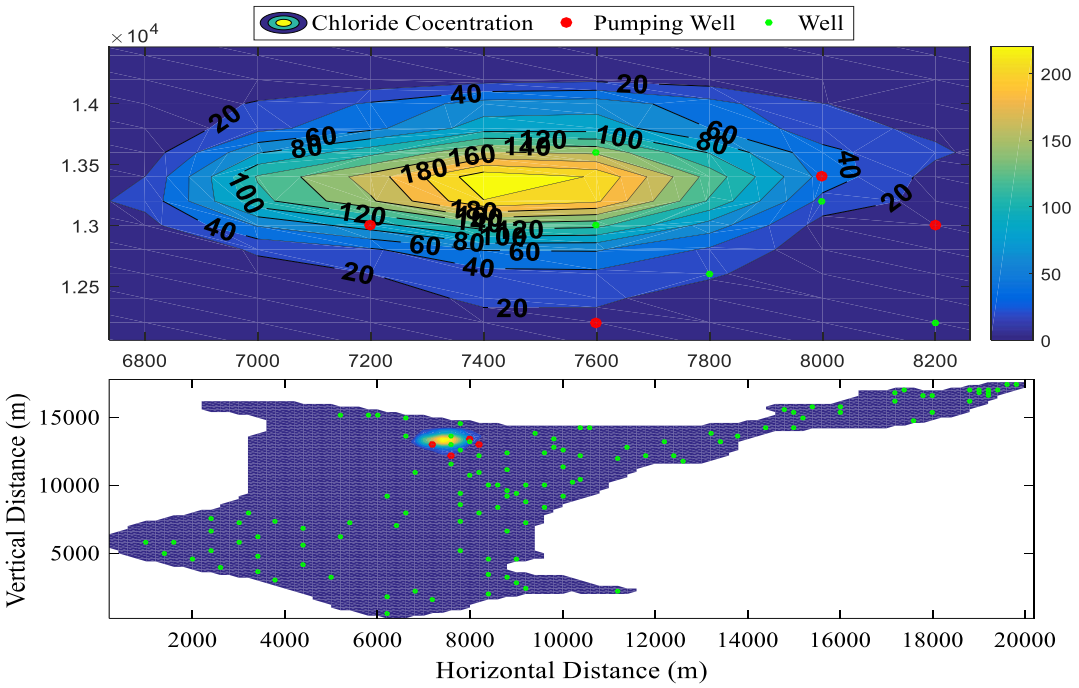


Fig. 15- Chloride concentration after 140 days remediation (MOPSO)

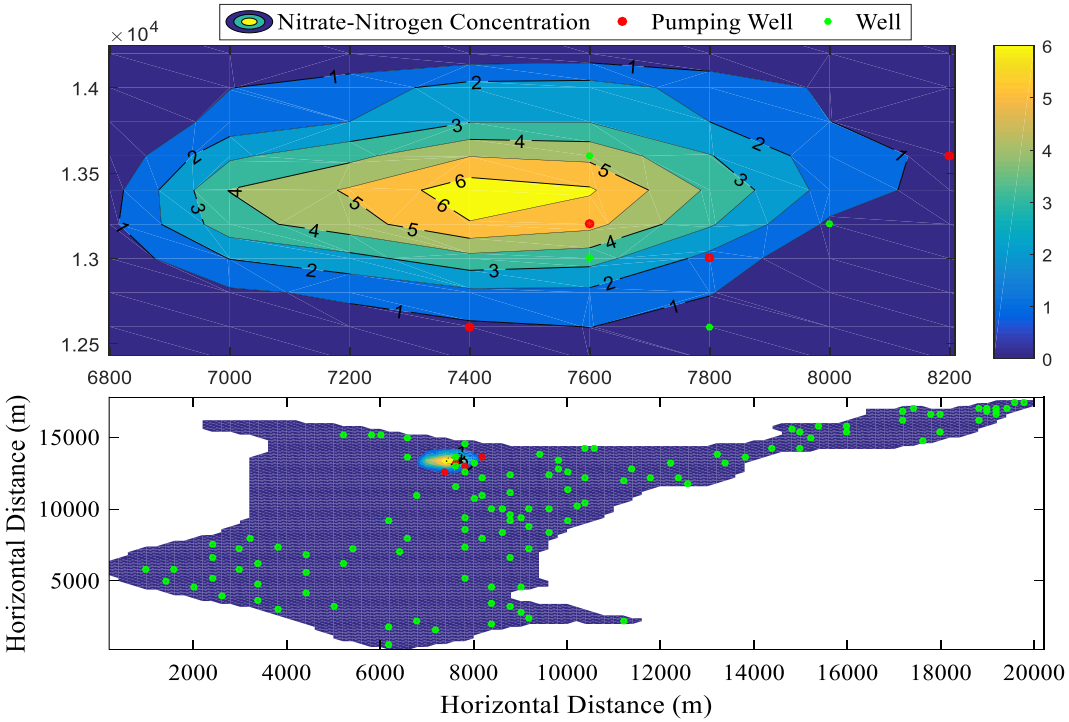


Fig. 16- Nitrate-Nitrogen concentration after 126 days remediation (MOMVO)

As can be seen in Figures (15) and (16), none of the pumping wells are located on the pumping well for agricultural use. It is also observed that pumping wells with agricultural use are in the path of pollution and are affected by pollution. However, pumping from these wells can reduce the contaminant concentration. But the pumped water needs to be treated. Therefore, it is recommended not to pump from these wells during the remediation period so that the contaminant concentration reaches the permissible limit of contaminant concentrations.

Conclusion

In this study, development of hybrid S/O models, multi-verse-meshfree (MV-MF) simulation-optimization and multi objective multi-verse meshfree (MOMV-MF) simulation-optimization are used to solve a groundwater remediation problem in pump and treat (PAT) system. These two models are compared with particle swarm meshfree (PS-MF) simulation-optimization and multi objective particle swarm meshfree (MOPS-MF) simulation-optimization. The Ghaen aquifer is investigated in three optimization problems.

In one-objective optimization problems we used four pumping wells with a rate of 800 m^3/day to minimize the mean of contaminant concentration. The results indicated that the MV-MF and PS-MF models have same performance. But PSO algorithm is trapped in local optimum. Besides, the MVO algorithm, with its special theory of traveling objects between two universes, can easily move from one part of the search space to another.

In the two-objectives problem, the mean of pumping rate was also considered. The optimization problem was investigated with four pumping wells at a variable pumping rate of [500,800] m^3/day. The results indicated that the number of solutions in the pareto-front in MOMVO was higher than MOPSO. In the last step, three-objectives problem was also examined, in which the third objective function was minimizing the remediation period. The results of MOPSO and MOMVO algorithm indicated that by changing the PAT policy, the 3 years (1095 days) remediation period can be reduced to 1.4657 and 1.4384 years (535 and 525 days), respectively.

Generally, MVO algorithm had good performance compare with PSO algorithm to solve the groundwater remediation optimization problem because of the special way the algorithm works in move the objects between different universes. Assumption, due to numeration nodes from bottom to top (or any direction) for a hypothetical aquifer with a structural grid in 20×100, nodes are in bottom and top of node "A" with node number=50 is 49 and 51, respectively. Also, nodes are in left and right of node "A" are 30 and 70, respectively. While distance between these nodes and node "A" is equal in regular grid of points. However, in MVO algorithm, the objects are nodes number and they can easily move between different universes but nodes number change in PSO algorithm by velocity vector and high and low value for maximum velocity in velocity limits can eliminate some of nodes in near vicinity of the node "A" or far away from node "A" that maybe good choice for pumping well location. Therefore, it is recommended to use MVO algorithm to solve groundwater remediation optimization problems.

Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

Confirmation

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contribution

Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, and writing—review and editing, visualization: M.J.Z, M.N.T, O.M

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